Exhibit 3-4

Globalstar MES GLONASS Interference Assessment

Parameter	**Value**	**Units**	**Notes**
Transmitter Power (Total)	24.0	dBm	0.3 Watts nominal power level; BW = 1.23 MHz
GNSS RFI power density	-54.0	dBc/MHz	Noise density rel. to carrier
GLONASS channel filter	-3.5	dBMHz	Convert to Prfi in GLONASS channel (Equiv. Rectangular noise BW = 461 kHz)
Antenna gain (toward GNSS user)	0.0	dBi	Quasi-omni antenna pattern
Equivalent Transmit EIRP in RFI	-33.5	dBm	
Space loss	-76.6	dB	range = 100 meters
Shielding/Shadowing	0.0	dB	
GNSS user ant. gain @ RFI	-5.0	dBi	
Received Carrier Power (MES)	-115.1	dBm	
Received Carrier Power (GLONASS)	-135.5	dBm	Min. specified value
Effective C/I	-20.4	dB	
Required C/I	-22.0	dB	Max tolerable C/I for RFI BW > 600 Hz
Margin	1.6	dB	

Exhibit 3-1 are as follows: (1) the calculation leading to equivalent EIRP in transmitted RFI is based on a 461 kHz equivalent rectangular filter; (2) the GLONASS received carrier power is reduced 5.5 dB relative to GPS; and (3) the required J/S is reduced 2 dB relative to GPS. The result is a nominal link margin of 1.6 dB at a range of 100m.

As with GPS, we can apply a probabilistic analysis to evaluate potential impact of variable or poorly known link budget parameters. The analysis presented in Section 3.1 is relevant for GLONASS, and again leads to an improvement in expected margin of 4.5 dB with a standard deviation of 3.6 dB. However, in this case the expected margin after adjustment is only 6.1 dB (versus 10.6 dB in the case of GPS) and the probability of degraded operation is therefore closer to 5%. As with GPS, "degraded operation" refers here to a receiver operating on one or more GLONASS channels at J/S > 22 dB. Loss of signal tracking may or may not occur in any particular instance.

For cases where intermodulation products dominate, the probability of degraded operation will be higher than 5%. Since this probability depends on the relative frequency offset between the MES channel assignment and the GLONASS channel ID, and the GLONASS frequency plan is in a state of flux, the overall probability of degradation for a randomly-selected GLONASS channel must be determined parametrically as a function of the GLONASS frequency plan. Exhibit 3-5 tabulates expected margin for each frequency assignment pair. Exhibit 3-6 tabulates the resulting probability of degraded operation for each frequency assignment pair (based on a standard deviation of 3.6 dB). Finally, averaging these probabilities over each alternative frequency plan leads to the following results:

a. Current plan. 11.7%

b. Antipodal (1, 12) plan. 5.3%

c. Antipodal (-6, 6) plan. 4.5%

The conclusion is that , under the current frequency plan, there is a probability of approximately 12% that a GNSS Receiver tracking a rancomly-selected GLONASS channel, operating 100m away from an MES operating on a randomly-selected Globalstar channel, would perceive a J/S ratio that exceeds ARINC characteristic 743A-1 specifications. For both antipodal schemes, the probability is closer to 5%. Loss of signal tracking may or may not occur under these circumstances.

Exhibit 3-5: Expected Link Margin for GLONASS Signals

MES Operating in Channel #	Link Margin for GNSS Signal in GLONASS Channel																					
	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	22	23	24
1	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.5	0.5	-2.3	-5.1	-7.9	-0.9	1.3	1.6
2	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	0.9	-1.7	-7.1	-4.3	-1.4
3	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	-23.4	-10.4	-7.6
4	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	-52.5	-52.1	-36.1
5	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	-11.4	-42.3	-52.4
6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	-5.3	-8.1	-10.9
7	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	0.7	-1.9	-4.7
8	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.1
9	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
10	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
11	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
12	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
13	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6

SH684

Exhibit 3-6: Probability of Exceeding J/S Specification for GLONASS

MES Operating in Channel #	Pr {J/S exceeded} for GNSS Signal in GLONASS Channel																					
	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	22	23	24
1	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.083	0.271	0.57	0.831	0.162	0.051	0.045
2	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.066	0.225	0.767	0.478	0.201
3	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	1	0.952	0.81
4	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	1	1	1
5	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.974	1	1
6	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.59	0.844	0.964
7	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.072	0.241	0.532
8	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.059
9	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
10	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
11	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
12	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
13	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045

SH685

Section 4
Operational Impact of MES-Induced RFI on GNSS Navigation

This section addresses the operational impact of MES-induced RFI on GNSS navigation, given the probabilities of signal impairment calculated in Section 3, and various operational scenarios based on user phase of flight.

4.1 General Considerations

Effective navigation based on GNSS requires sufficient numbers of satellites in good geometry to provide acceptable Dilution of Precision (DOP), as well as receiver autonomous integrity monitoring (RAIM) and failure detection/isolation (FDI) if the user is operating without a differential overlay. Exhibit 4-1 illustrates Horizontal DOP (HDOP) for GPS plus various numbers of geosynchronous spacecraft, as would be provided by a WAAS, assuming the user employs barometric input required by TSO C129. The lowest curve is provided for comparison purposes only; it corresponds to GPS alone without barometric input. The highest dashed curve (almost completely obscured by the solid curve) corresponds to the CONUS-average HDOP distribution with GS's at 60 degrees West and 100 degrees West.

For the data presented, GPS spacecraft were assumed to fail according to probability rules given by Durand and Caseau Set 5, so the results account for the expected losses of performance due to GPS failures and downtime. GS satellites were assumed to fail according to statistics based on historical Inmarsat experience and analytic projections for Inmarsat III. The underlying statistics for GPS and GS operating status are provided in Exhibit 4-2[3].

The virtual overlap between the curve for no GS failures in Exhibit 4-1, and the composite curve generated by the weighted average of the three dashed curves, attests to the high reliability expected of the GS spacecraft. Note that barometric input alone is sufficient to yield HDOP < 10 with availability greater than 0.99999. Note also the relatively even spacing between curves; in the tails of the distributions, each GS adds roughly one additional "9" to overall availability at a given DOP requirement. Furthermore, barometric input is seen to act essentially like another GS from the standpoint of availability.

Exhibit 4-3 illustrates the impact of adding additional satellites to a 24 satellite GPS constellation, from the standpoint of visibility statistics. The upper panel is baseline data for GPS taken from the GPS SPS Signal Specification; the lower panel is from Misra, et. al., and addresses augmentations of two geosynchronous spacecraft, six additional GPS spacecraft (one additional satellite per plane), and 12 additional GPS spacecraft (two additional spacecraft per plane). Note the difference in mask angles between the baseline GPS data and the augmented systems. The 7.5 degree mask employed by Misra, et. al., is somewhat conservative by current standards. Comparing the GPS24+2GS with the GPS-30, we see that the visibility statistics are roughly equal for 6 and 7 satellites in view, and that the GPS24+2GS leads to a somewhat more compact distribution relative to the GPS-30, which has to contend with variability due to rising and setting satellites. Thus, at the "low end" of the distribution, where performance requirements are most problematic, 2 GSs

---

3. It should be noted that these data represent several months of software development/modification and engineering anlysis, over which time several Gigabytes of data were collected. The Exhibits represent various weighted averages of tens of thousands of separate Monte Carlo trials, each trial consisting of nearly twenty thousand spatio-temporal grid points over CONUS. GNSS performance analysis under realistic failure rates is a time consuming proposition!

Exhibit 4-1

Composite HDOP Availability Distribution in CONUS with GPS + Baro + 2GS in Ideal Deployment

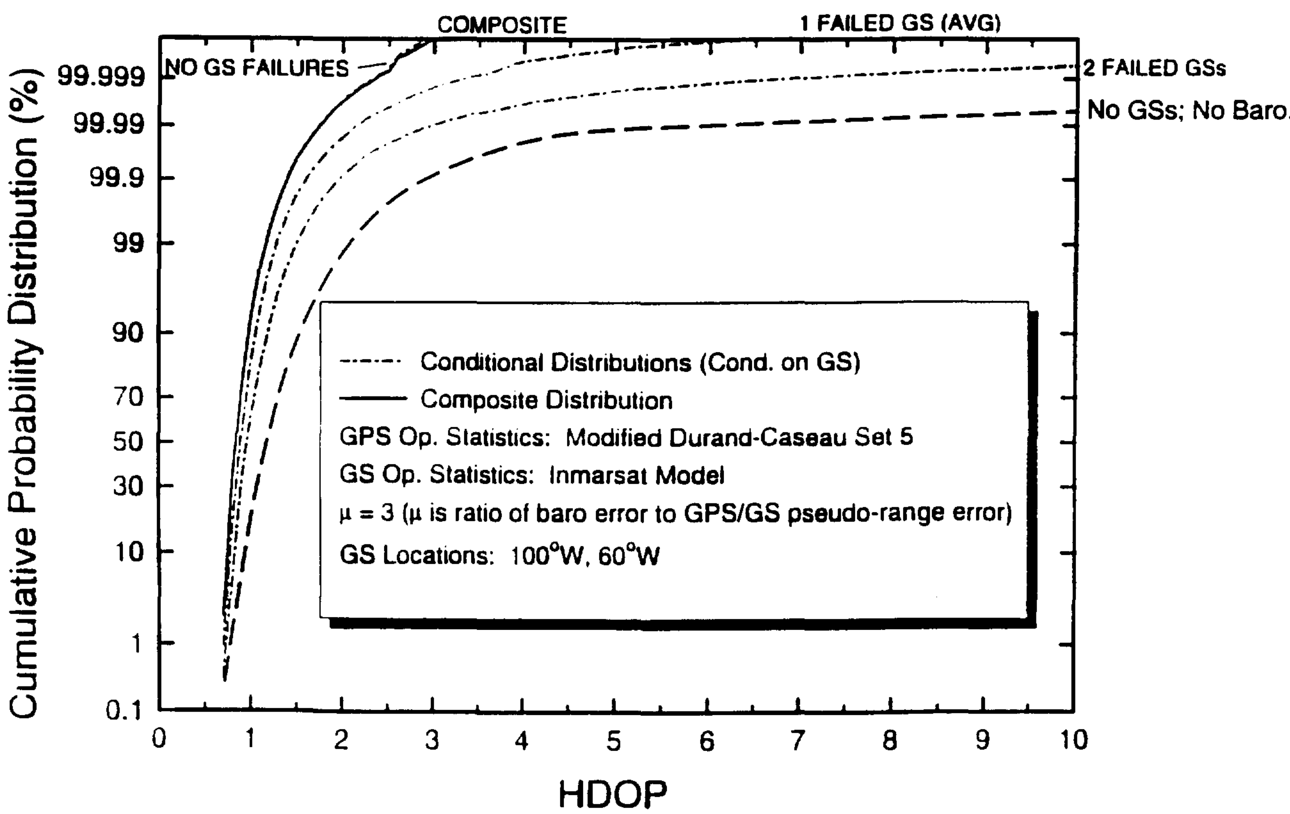


Exhibit 4-2
GPS and GS Reliability Statistics

4-2A GPS Reliability Statistics

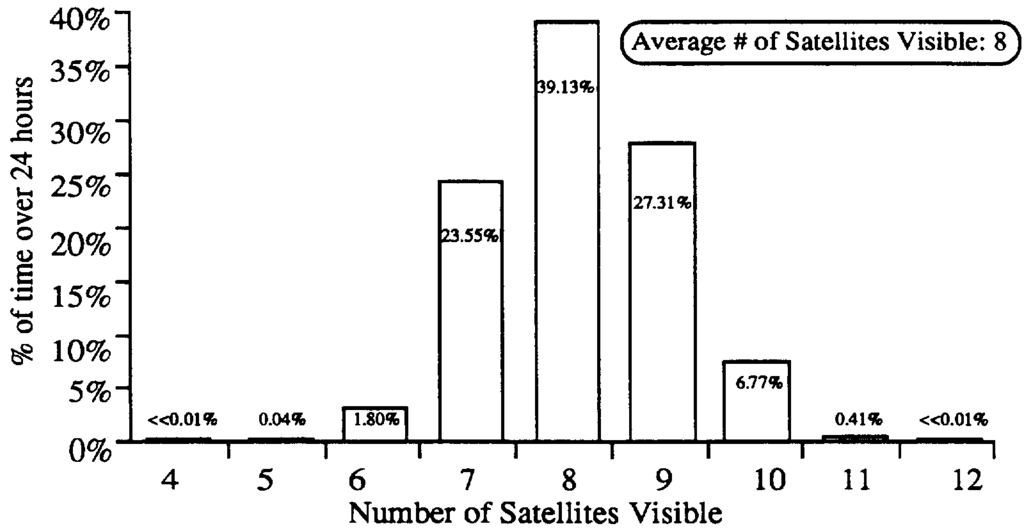
Operational SV's	Failed SV's	Prob.	Cumulative Prob.
24	0	0.700547	0.700547
23	1	0.236891	0.937438
22	2	0.050393	0.987831
21	3	0.010005	0.997836
20	4	0.001806	0.999642
19	5	0.000303	0.999945
18	6	4.75E-05	0.999992
17	7	6.99E-06	0.999999
16	8	9.67E-07	1

4-2B Geostationary Satellite (GS) Operational Probabilities

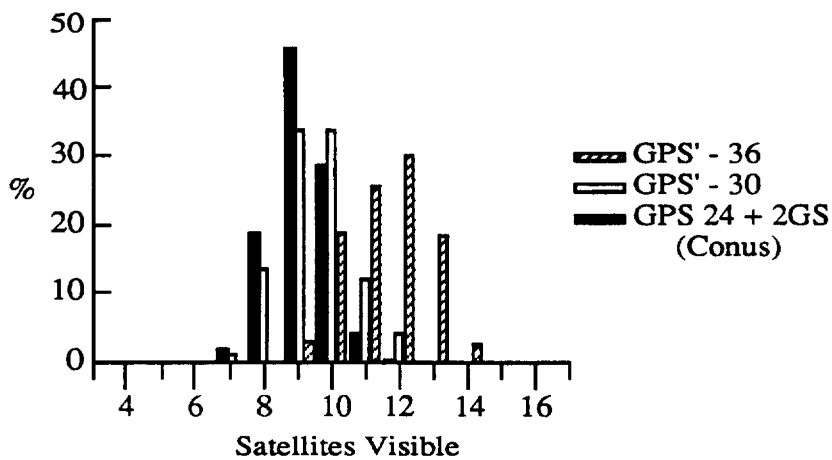
No. of GS Operational	No. of GS SVs Failed	Prob.	Cumulative Prob.
2	0	0.981110	0.981110
1	1	0.018755	0.999865
0	2	0.000135	1.000000

Reference: R. Phlong and B. Elrod, **Availability Characteristics of GPS and Augmentation Alternatives**, *Navigation*, Spring 1994.

Exhibit 4-3.
Availability and Visibility of HDOP
vs. Constellation Size



4-3A. Satellite Global Visibility Profile



4-3B. Availability vs. Constellation Size

Reference: P. Misra et al., op. cit.

are roughly equivalent to 6 additional GPS spacecraft (a ratio of 1:3). Qualitatively, this can be seen to be reasonable since each GPS spacecraft contributes roughly 8 hours of visibility (at a given ground site) per 24, while a GS contributes a full 24 hours of visibility.

Misra, et al.[4], extended the results of Exhibit 4-3 by considering the integrity level that could be "protected" with candidate algorithms for Receiver Autonomous Integrity Monitoring (RAIM). The results are illustrated in Exhibit 4-4. Again, note the close similarity between the GPS24+2GS constellation and the hypothetical GPS-30 constellation. For these constellations, an integrity protection limit of roughly 500 meters could be satisfied roughly 99.9% of the time. Note that, for this analysis, the GS relays in the GPS24+2GS constellation provide ranging signals, but no ground-based integrity data or differential corrections.

TSO'd GNSS receivers will be aided by barometric data; the number of independent measurements available for RAIM and Fault Detection/Isolation (FDI) is therefore one greater than the number of spacecraft visible at any given time. Reinterpreting Exhibit 4-3 in light of barometric aiding and a downward adjustment in mask angle to 5 degrees, we conclude that either a GPS24+2GS+baro system (as is contemplated for domestic US airspace), or a minimum of 30 GPS spacecraft + baro, would yield a minimum of 8 measurements at any time exclusive of satellite failures. It seems likely that the curves in Exhibit 4-4 would also be "lifted" by about one "9" , although this contention should be validated with actual analysis.

The data in Exhibit 4-1 accounted for expected failure rates in the GPS and GS constellations, but the data in Exhibits 4-3 and 4-4 assume perfect health by all satellites. As a result, these data are optimistic to an unknown degree. Refinement to include expected failure rates would require extensive Monte Carlo simulation runs designed to capture a representative sampling of the most likely failure modes.

Exhibit 4-5 illustrates typical visibility and HDOP performance, again from Misra, et al., for GPS+GLONASS assuming three random satellite failures in each constellataion (a total of six failures). GPS-only data is provided for comparison. The dual constellation exhibits substantial capability even after accounting for random failures. A minimum of 9 satellites are always visible. This represents a lower bound on performance for several reasons. First, the basic assumption of 3 satellite failures in each constellation puts these data at the "tail" of the probability distribution. As indicated previously in Exhibit 4-2, the GPS constellation alone expects to have 2 failures or less 98% of the time. Furthermore, Exhibit 4-5 assumes a user mask angle of 7.5 degrees, and no benefit from barometric aiding. Nevertheless, these data provide a starting point for analysis.

In terms of signal tracking capability, the following assumptions are applied based on the results of Section 3, unless stated otherwise:

1. Nominally, GPS and GLONASS signal tracking is not affected by MES operations at 100m.
2. At a range of 100m, the estimated probability of operation at J/S ratios greater than ARINC 743A-1 specifications is 0.2% for GPS.
3. At a range of 100m, the estimated probability of operation at J/S ratios greater than ARINC 743A-1 specifications is 5% for GLONASS (antipodal frequency plan, either 1-12 or -6 to 6, is assumed for the timeframe of Globalstar operations).

With this background on typical GNSS performance, it is now possible to address specific phases of flight.

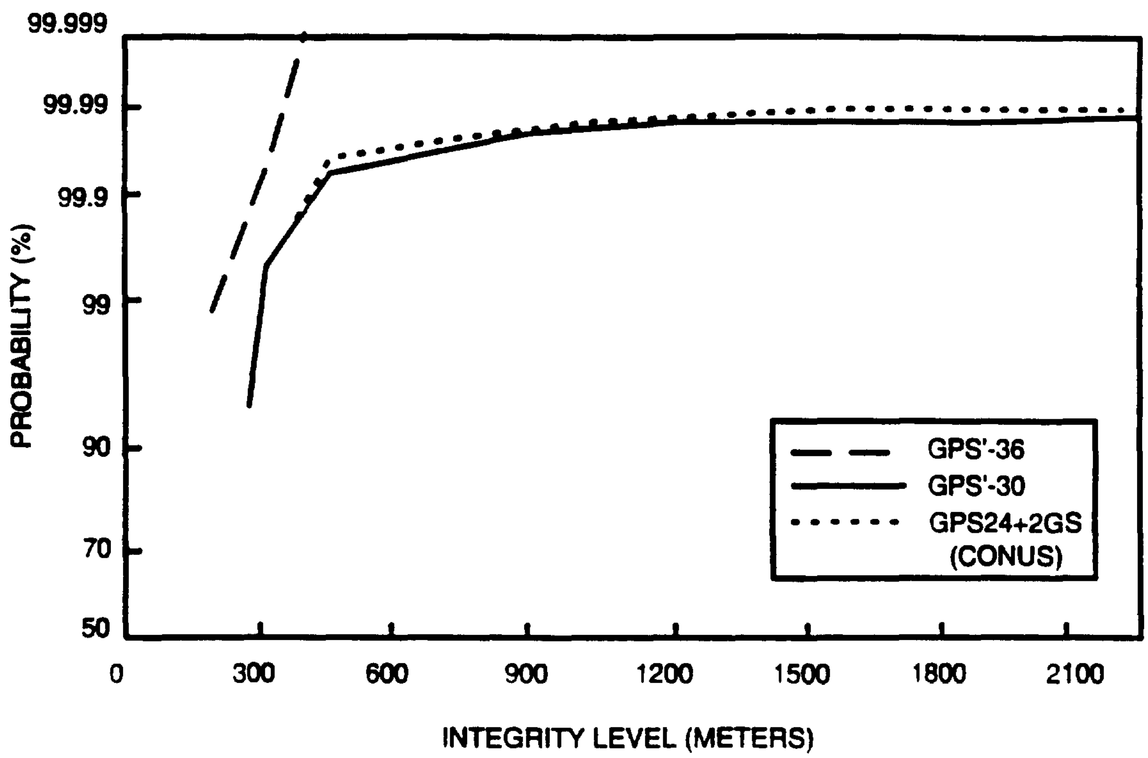
---

4. P. Misra, et. al., "Receiver Autonomous Integrity Monitoring (RAIM) of GPS and GLONASS," **Navigation**, Spring 1993.

Exhibit 4-4.

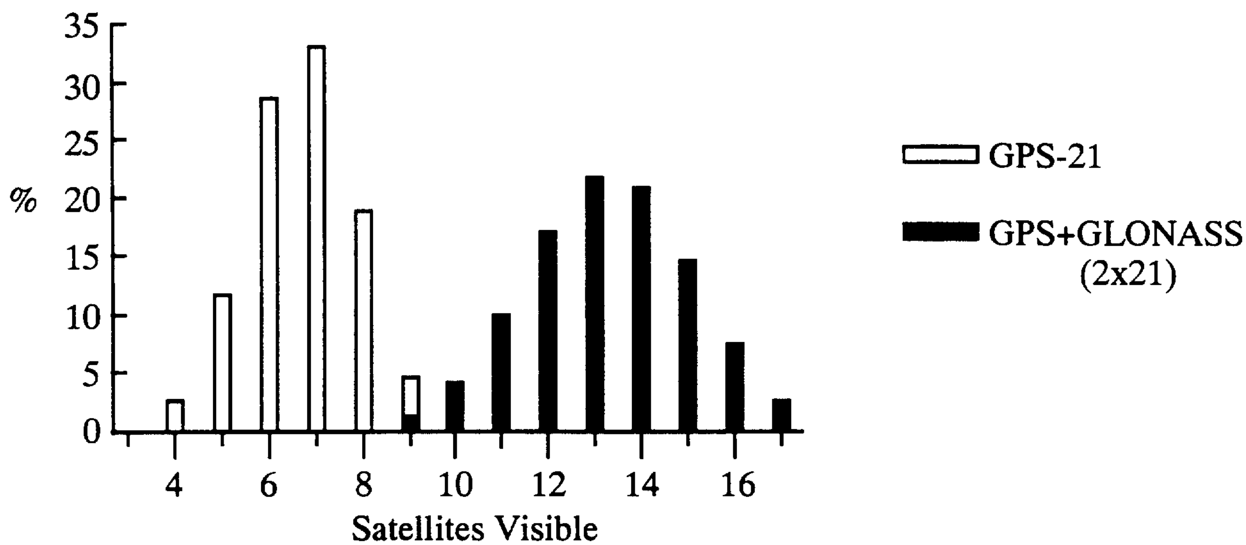
Availability of GNSS Navigation with Integrity (SA on)

Integrity Level (meters) with SA



Reference: P. Misra et al., op. cit.

Exhibit 4-5
Satellite Visibility Statistics for GPS and GLONASS



Reference: P. Misra, et al., op. cit.

SH691

4.2 En Route and Terminal Area Operations

Sole means navigation in the en route and terminal area airspace requires a navigation system that can deliver fault-free 95% accuracy of 0.124 nmi (horizontally), with integrity, at availability levels of 0.99999. In US airspace, GNSS equipment must include altimeter aiding to enhance availability with integrity. Nevertheless, GPS plus altitude input alone is insufficient to achieve sole means performance. R. Grover Brown, et. al.[5], determined that, for one candidate integrity assurance algorithm, availability with fault detection capability within the United States would be about 99.9% for terminal area operations. Availability with fault detection and isolation (implying a "fail-operational" capability) was only 94.3% for terminal area operations.

To achieve availability levels of 0.99999, augmentation with GLONASS or geosynchronous satellites is required. In the US, the FAA is energetically pursuing development and deployment of a WAAS in order to support sole means navigation. This system will nominally provide at least double coverage by geosynchronous spacecraft everywhere in the continental US. As noted above, Misra, et. al.,[6] determined through numerous simulations that two visible geosynchronous satellites are sufficient (barely) to satisfy sole means requirements on availability and integrity (These analyses assumed a mask angle of 7.5 degrees, no integrity broadcast and no differential corrections through the GS's, and no use of barometric aiding. Current FAA and aviation industry planning would imply substantially better performance).

On the other hand, Misra's analysis ignored the effects of satellite failures for the cases reported above. This will offset, to some modest extent (TBD), the performance gains associated with lower mask angle, integrity and possibly DGPS corrections, and baro aiding. An overlay of two geosynchronous spacecraft was also found to be roughly equivalent, from a RAIM standpoint, to six additional GPS spacecraft. This rough correspondence can be used to assess the impact of losing some portion of the GLONASS constellation due to RFI.

What is the operational impact of RFI on a GPS+WAAS or GPS+GLONASS system? As indicated earlier in Section 3, nominal operations by an MES will not degrade GPS operations (or WAAS operations, which are on the same frequency) at a range of 100m. There is a small chance that an MES operating in a shadowed mode could degrade a GPS receiver operating at a range of 100m; however, it is unlikely that an aircraft would operate that close to the ground for normal en route or terminal area operations (Flight below 500 feet (152m) is disallowed in populated areas, so a 100m separation between an aircraft and an MES would have to be accidental. By comparison, the Minimum Descent Altitude during non-precision approach is 250 feet above terrain, or 76m. A 100m vertical separation would place the aircraft in the final stages of an approach, as opposed to en route or terminal area operations).

Assuming an aircraft is actually operating at an altitude of 100m, and that it passes directly over an MES operating in a shadowed mode (but the shadowing does not reduce the flux density impinging on the aircraft), and assuming a relatively slow ground speed of 33 meters/second (75 mph), and taking no credit for airframe blockage/shielding (despite the earlier assumption of a perfect overhead pass), the MES could potentially degrade GPS+WAAS signal tracking with a

---

5. R. Grover Brown, et. al., **Assessment of RAIM FDI Availability Using ARP Method of Screening Out Bad Geometries,** US Department of Transportation , Volpe Center, Cambridge MA. RTCA paper No. 213-93/SC159-436, May 1993.
6. P. Misra, et. al., **Receiver Autonomous Integrity Monitoring (RAIM) of GPS and GLONASS,** ***Navigation***, Spring 1993.

Exhibit 4-6

OUTAGE TIME CALCULATION FOR GNSS RCVR AFFECTED BY GLOBALSTAR MES

ASSUMPTIONS:

1. Direct overhead pass
2. GNSS signals at minimum specified levels
3. GPS signal tracking lost at average C/I = -24 dB
4. No MES signal blockage by airframe

$d := -0$	d is the MES duty cycle in dB
$Noise := -20.5$	Maximum RFI power level in dBm for shadowed operation
$Dir\_gain := -5$	Directive gain of GNSS antenna toward MES
$EIRP := Noise + d$	EIRP is expressed in dBm
$Velocity := 33.36$	Aircraft ground speed in meters/sec (100km/hr = 27.8 m/s)
$height := 25, 50 .. 300$	Aircraft height above terrain

$$Req\_space\_loss := -106 - EIRP - Dir\_gain$$

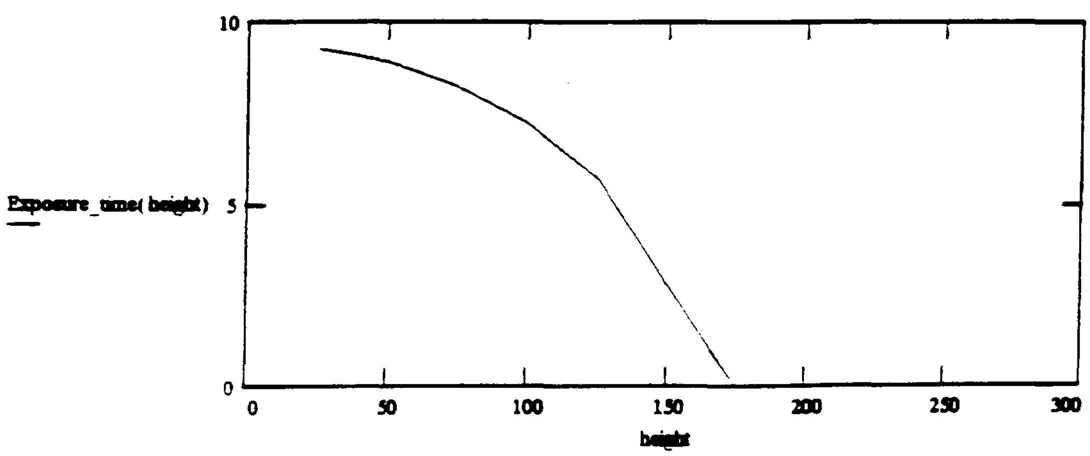
$$Req\_space\_loss = -80.5$$

$$Threat\_radius := 10^{\left(\log\left(\frac{0.186335}{4\cdot\pi}\right) - \frac{Req\_space\_loss}{20}\right)}$$

$$Threat\_radius = 157.067$$

$$Exposure\_distance(height) := 2\cdot\sqrt{\left(Threat\_radius^2\right) - height^2}$$

$$Exposure\_time(height) := \frac{Exposure\_distance(height)}{Velocity}$$



conditional probability of ~0.2 %. The period of degradation would not exceed 7 seconds (see Exhibit 4-6). This is shorter than the alarm time constraint of 30 seconds for terminal area operations, indicating no operational impact even for this highly contrived and unrealistic case.

For GPS+GLONASS, a slow low-altitude pass directly over a shadowed MES (which injects RFI as if there were no shadowing and no airframe shielding) could potentially degrade the signal tracking in the GLONASS channels of the GNSS receiver for a period of 20-22 seconds (see Exhibit 4-7). The probability of this event, conditional on all prior assumptions, is about 5%. If GLONASS signal tracking were actually lost during this time period, the user's ability to detect or isolate a satellite failure could be degraded. However, for en route and terminal area navigation, a user can "coast" through a short-term loss of his/her ability to isolate a failure as long as the fault detection capability is retained. Thus, we can apply the GPS+baro availability statistic for fault detection of 99.9% to determine the exposure risk. This implies that, averaged over all points in the continental US and all times, there is a probability of 0.001 that a pilot might be in a situation where GLONASS is needed to retain a navigation capability after allowing for short-term coasts of integrity/isolation. The probabilistic link budget analysis for GLONASS indicated a potential risk of 5% at 100m (TBR). In actual practice, some GLONASS channels will perceive higher risk than others due to: (1) proximity to the MSS band; and (2) GLONASS signal level variations. However, if GLONASS support is artificially modeled as a binary random variable, we would require the probability of extremely low altitude operations in a populated area to be 20% or less, to conclude that there is no operational impact in this phase of flight. This is indeed the case, implying that there is no operational impact.

4.3 Non Precision Approach Operations

The FAA has already certified GPS with barometric altimeter aiding for supplemental use and planned sole means use down to NPA minima. The GPS+WAAS will satisfy sole means requirements down to this level as well. If high-accuracy differential corrections are available through the WAAS, GPS+WAAS will actually support Category I precision approach, although the projected availability may be closer to 0.999. Prior availability studies by numerous investigators supports the conclusion that GPS+2 or 3 geosynchronous spacecraft will support NPA requirements.

As one example, Exhibit 4-8 illustrates summary data generated by Phlong and Elrod. Both the accuracy and integrity protection limits are satisfied by 2 GS and 3 GS augmentations to GPS, for the pseudorange errors mandated for the system. For this analysis, the geosynchronous spacecraft were treated as sources of ranging data only; all GPS and GS spacecraft were also subjected to failure rate statistics consistent with historical data, and barometric aiding was neglected.

Since the performance impact of each additional GS is essentially equivalent to three additional GPS spacecraft (or a somewhat greater number of GLONASS spacecraft), we can conclude that NPA operations are satisfied under nominal conditions with GPS plus roughly one quarter to one half of the GLONASS constellation.

One potential issue for a GPS+GLONASS system supporting NPA operations is Continuity of Service. The NPA requirement for Continuity of Service is in flux, and could be as low as 0.9999 or as stringent as $(1\text{-}10^{-8})$/hour. Also relevent is the integrity alarm time of 10 seconds, which places an upper bound on the coast time allowed by the operational environment. As indicated previously by Exhibits 4-6 and 4-7, high power MES emissions have the potential to degrade GNSS receiver tracking performance for 7 seconds (GPS signals) and for approximately 20 seconds (GLONASS signals), respectively. The probabilities of these events at a range of 100m are 0.2% and 5%, respectively, under conservative assumptions. The 7 second exposure time for GPS signal tracking is below the 10 second alarm time constraint. When combined with a) the low

Exhibit 4-7

OUTAGE TIME CALCULATION FOR GNSS RCVR AFFECTED BY GLOBALSTAR MES

ASSUMPTIONS:

1. Direct overhead pass
2. GNSS signals at minimum specified levels
3. GLONASS signal tracking lost at average C/I = -22 dB.
4. No MES signal blockage by airframe

$d := -0$	d is the MES duty cycle in dB
$Noise := -20.5$	Maximum RFI power level in dBm for shadowed operation
$Dir\_gain := -5$	Directive gain of GNSS antenna toward MES
$EIRP := Noise + d$	EIRP is expressed in dBm
$Velocity := 33.36$	Aircraft ground speed in meters/sec (100km/hr = 27.8 m/s)
$height := 25, 50 .. 300$	Aircraft height above terrain

$$Req\_space\_loss := -113.5 - EIRP - Dir\_gain$$

$$Req\_space\_loss = -88$$

$$Threat\_radius := 10^{\left(\log\left(\frac{0.186335}{4\cdot\pi}\right) - \frac{Req\_space\_loss}{20}\right)}$$

$$Threat\_radius = 372.464$$

$$Exposure\_distance(height) := 2\cdot\sqrt{\left(Threat\_radius^{2}\right) - height^{2}}$$

$$Exposure\_time(height) := \frac{Exposure\_distance(height)}{Velocity}$$

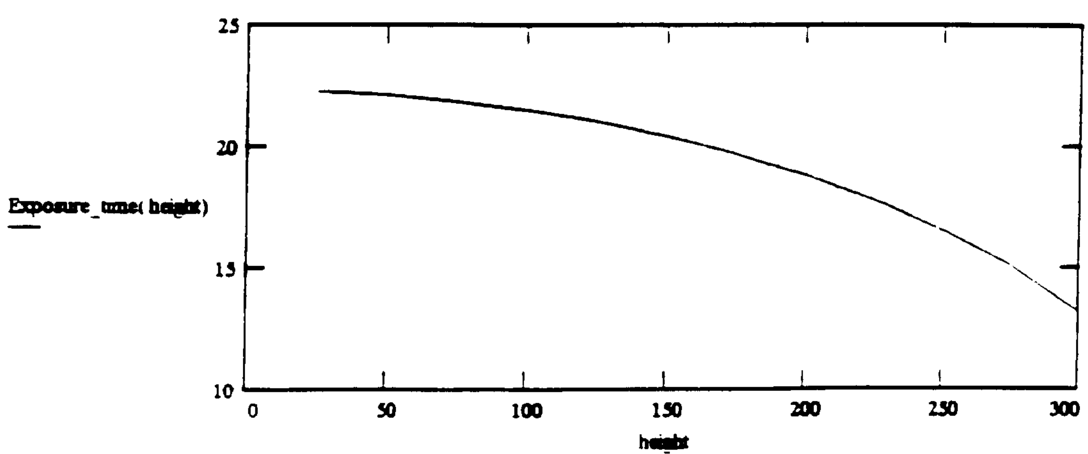
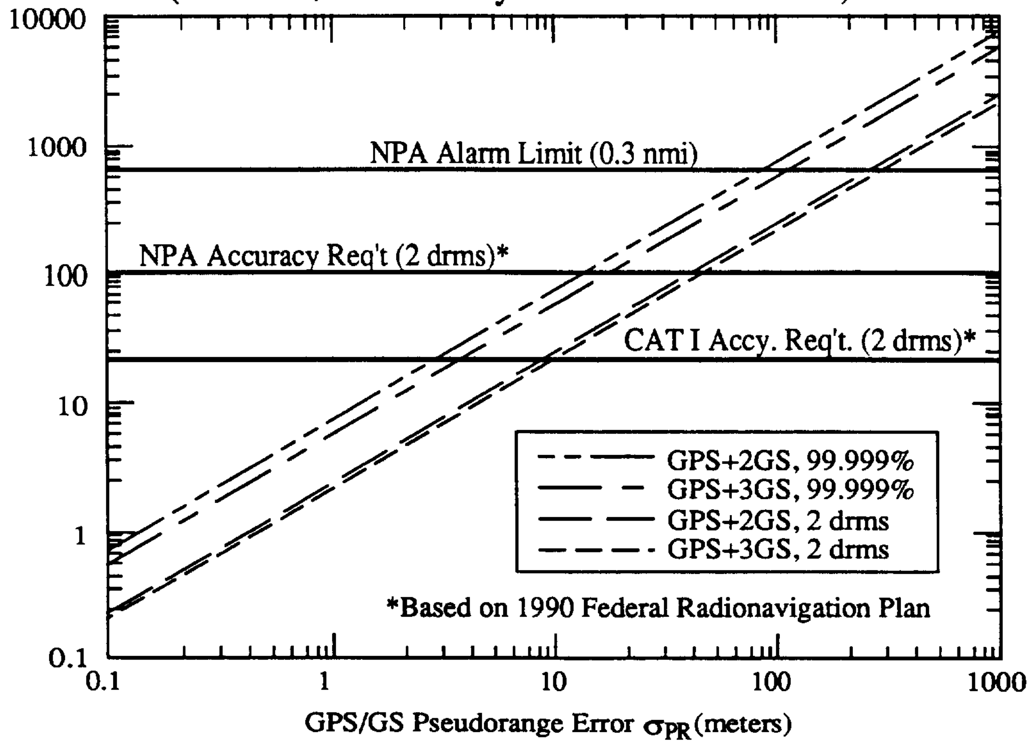


Exhibit 4-8: Horizontal User Navigation Performance

(GPS + 2/3 GSs in Symmetrical Locations)



ref.: Phlong and Elrod, "Availability Characteristics of GPS and Augmentation, "ION National Technical Meeting, January 1993 probability of occurence, b) the conservative assumptions, and c) the potential for continued signal tracking and acceptable navigation performance, even in the event of J/S threshold excedance, it seems reasonable to conclude that the potential for GPS signal tracking impairment is not operationally significant for NPA.

For GLONASS, the potential exposure time of 20-22 seconds is twice the time to alarm, and the probability of occurance is 25 times higher than for GPS. However, TSO C-129 allows coasting of RAIM for up to five minutes as long as a pre-approved check was performed, and the navigation function is preserved. Thus, as long as GPS + baro can provide a navigation solution, the chance of losing integrity due to GLONASS signal tracking is acceptable. Young Lee has shown that GPS+baro provides essentially 100% availability of navigation, even with up to three failures in the GPS constellattion. Furthermore, as noted above, even the most conservative assumptions regarding MES impact on GPS signal tracking imply an exposure time (for GPS) of 7 seconds or less. This indicates that MES emissions have no operational impact on NPA operations. Nevertheless, further analysis may be warranted to refine the availability statistics for GPS+baro, as well as the link budget assumptions and analyses. It may be necessary to extend the results to eight significant digits, in order to demonstrate no operational impact relative to the potential NPA continuity of Service specification of ($1\text{-}10^{-8}$/hr).

4.4 Category I Precision Approach Operations

Category I precision approach operations absolutely require some form of differential overlay, such as the WAAS or a local area differential system. A WAAS or local-area differential system is a necessary and sufficient augmentation to GPS to satisfy Category I approach requirements. GLONASS may be employed as an adjunct to enhance availability, but is not required. Thus, from an availability standpoint, complete loss of GLONASS can be tolerated without incuring a significant operational penalty. On the other hand, as with NPA, continuity of service is a key parameter of required navigation performance in precision approach operations. Continuity of service is important because a loss of navigation service could force the pilot to execute a missed approach, and there is a small but nonzero safety risk associated with missed approach operations.

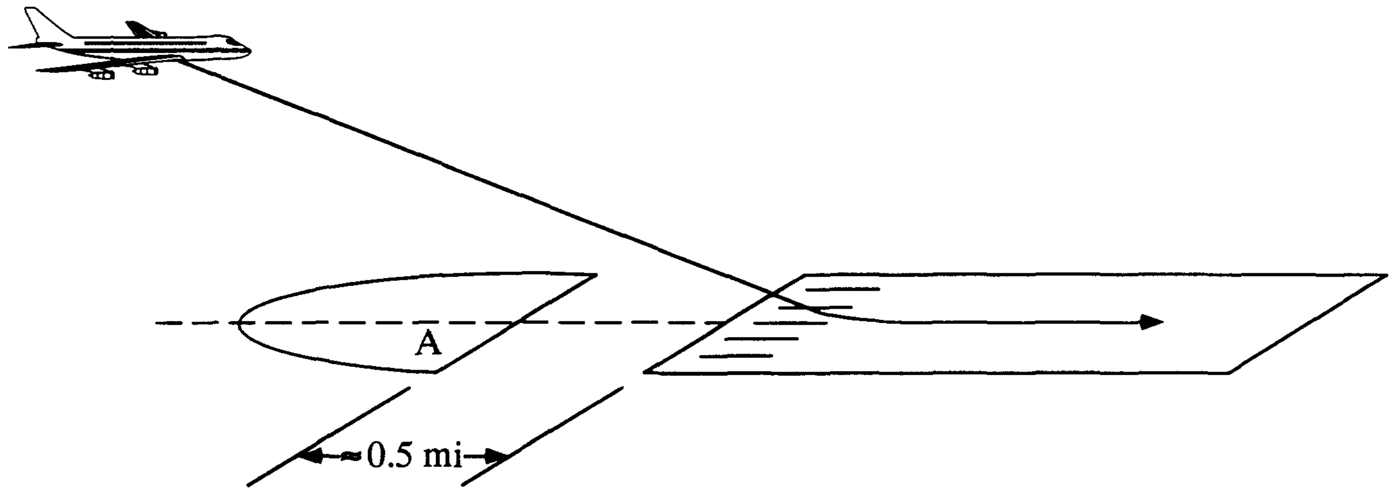
The Special Category I requirement for Continuity of Service is $6\text{x}10^{-5}$ over the duration of an approach (i.e., Final Approach Fix down to the 200 foot decision height). A continuity issue could arise if a strongly-emitting MES is situated close to a runway, essentially under the approach path, and manages to degrade GPS receiver performance for more than several seconds (the alarm time for Category I precision approach is 6 seconds). For an MES transmitting at full power, this would require placement within roughly 150 meters of the extended runway centerline, no closer than a half mile and no further than 1 mile from the runway threshold. The zone of potential influence is illustrated in Exhibit 4-9.

Assuming MES emissions at the maximum level for shadowed operations, GPS signal strength at the minimum specified level and GNSS antenna directive gain toward the MES at -5 dBi (despite the significant look-down angle implied by this scenario), actual interference also requires excess shielding/blockage between the MES and the aircraft GNSS antenna to be less than 6 dB. This combination of events is considered highly unlikely; nevertheless the probabilistic assessment of Section 3 indicated a potential probability of impairment of 2×10^{-3}. This would be unacceptable compared to the 6×10^{-5} required.

A continuity problem could also arise if a pilot begins an approach under a degraded GPS constellation, where the pilot relies on GLONASS to provide the necessary minimum number of ranging signals or geometry, and these signals become degraded during the approach due to RFI. (Note: in this scenario, GPS signal processing is unaffected, but GPS alone is insufficient to

Exhibit 4-9. Potential Interference Geometry for Category I Precision Approach

- MES in region "A"
- MES shadowed relative to best satellite
  - high power operations
- GNSS directive gain toward MES at -5 dbi; equivalent to on-horizon gain
- Airframe shielding ≤ 6 dB
- GPS signals at minimum levels



support the approach). In this situation, significant signal degradation could lead the avionics to declare an integrity alarm; the pilot would be forced to execute a missed approach if the alarm occurred before the pilot visually acquired the runway. Further analysis should be performed to assess the potential for signal tracking degradation, as well as the probability of impairment to the user's navigation function. If further analysis shows that navigation or integrity functionality can be degraded, one of the following response strategies could be adopted:

a. **Take availability penalty on GPS+GLONASS receivers.** Under this strategy, users with GPS+GLONASS receivers would limit their precision approach operations to those times and places where GLONASS was not required (i.e., the precision approach operation could be projected to completion based solely on the currently-available GPS spacecraft, barometric aiding and possible GS augmentations). The impact of this strategy on actual or calculated availability is TBD.

b. **Assume average constellation performance.** Under this strategy, one would argue that the vast majority of all approaches can be completed without GLONASS; therefore, an occasional missed approach due to loss of selected satellites is tolerable (it is no different from missed approaches due to poor flight technical error, bad weather, etc.). This strategy applies the Continuity requirement to the aggregate of all approaches rather than each approach individually. The policy impact of this strategy is TBD.

c. **Limit Globalstar MES emissions in the vicinity of airports supporting precision approach operations.** Under this strategy, MES's operating in beams that contain airports supporting GNSS-based precision approach operations would not be commanded to power levels that could impair GLONASS operations. The impact on Globalstar perceived quality of service is TBD.

d. **Limit Globalstar MES emissions by more elaborate out-of-band filtering.** Under this strategy, MES electronics would be augmented to provide additional isolation in the GNSS band. The impact on Globalstar MES costs is TBD.

4.5 Surface Operations

As with precision approach, surface operations absolutely require some form of differential overlay such as the WAAS or a local area differential system. A WAAS or local-area differential system is a necessary and sufficient augmentation to satisfy surface operation requirements -- especially accuracy. Integrity is provided by the differential overlay, and theoretical availability is at least an order of magnitude higher than in the terminal area because surface operations are inherently 2-dimensional (they require one less satellite assuming the GNSS receiver has pre-determined airport altitude, or has read this data from an on-board data base). GLONASS may be employed as an adjunct to enhance availability even more, but is not required. Thus, from an availability standpoint, complete loss of GLONASS can be tolerated without incurring an operational penalty.

Current airport operations do not generally depend on electronic navaids for surface navigation. Future operations may involve some fraction of the high-end air fleet acquiring this capability, but it is not likely to become required equipage in the foreseeable future. The availability of GNSS-based navigation for surface operations is essentially a cost/benefit issue rather than a safety of flight issue. The existence of GNSS may enhance traffic management efficiency on the airport surface in the future. If GNSS becomes an integral part of future surface navigation and traffic management systems, its absence or loss could degrade traffic management efficiency. It may also result in selected aircraft being forced to stop, and cease operations. On the other hand, as long as the pilots heed the directions of the ground controllers, safety will be maintained. Given a) the lack of defined availability standards for surface navigation, b) the lack of safety concerns, c) the exceptionally high availability of surface navigation even without GLONASS, and d) the general robustness of GPS signal processing relative to expected MES emission levels, there appears to be no significant issue or serious concern in the surface domain.

Section 5
Summary and Conclusions

5.1 Summary

An assessment of Globalstar MES emissions on GNSS receiver navigation performance has been performed. This assessment focused on the operational impact of MES emissions on user navigation performance relative to generally accepted standards of Required Navigation Performance (RNP) as a function of user phase of flight. Analytic refinement is possible and desirable in many areas:

1. **The definition of RNP is evolving.** Internationally, the ICAO RGCSP (Review of the General Concept of Separation Panel) and AWOP (All Weather Operations Panel) is attempting to forge a broad consensus on the definition of RNP. Domestically, the FAA is initiating an effort to redefine the basic requirements documents for the National Airspace System in terms of RNP. The precise definition of RNP and threshold levels for each phase of flight are being refined through analysis and consensus.

2. **MES operating characteristics are projections.** The characteristics assumed here are subject to refinement. In particular, substantial rolloff may exist in the far out-of-band MES emission spectrum (e.g., below the -54 dBc/MHz at $\Delta F \geq 4$MHz assumed here).

3. **GNSS receiver operating characteristics and performance requirements should be improved.**.The prior requirements were driven by formal specifications, which have tended to ignore advancements in technology and normal engineering margins. In particular, the analysis reported here assumes that navigation performance could be lost at J/S ratios that marginally exceed the ARINC Characteristic 743A-1 specifications. Therefore, upgraded specifications which would improve MSS sharing is required as discussed by ARINC at the NRM.

4. **GNSS constellation expected performance levels are projections.** As operational confidence in GNSS builds over time, and as historical experience dictates, assumed failure rates will be adjusted. Further analysis is also required to extend currently available performance data, which were derived from assumptions that do not precisely match projected GNSS operations scenarios or evolving certification requirements.

5. **Future GNSS receivers may incorporate enhanced signal rejection technologies.** The specifications for GNSS receivers that will operate in conjunction with WAAS, and provide primary means navigation capability via GNSS, are currently being developed. Interference assessment analyses are ongoing in the aviation community, and RFI mitigation techniques are being evaluated with an eye toward enhancing GNSS receiver robustness. These mitigations include filtering, revisions in the A/D circuitry and other changes.

In spite of these influences, an initial worst case MES impact assessment has been completed. The US requirement for barometric aiding (via TSO C-129) significantly improves the expected level of performance of the most disadvantaged user in US airspace. From a visibility standpoint, a full GPS constellation with two additional geosynchronous spacecraft is sufficient to satisfy all accuracy, availability and integrity requirements in all phases of flight except precision approach. If differential corrections are available through the geosynchronous spacecraft, Category I precision approach requirements can be satesfied as well. Similar performance can be achieved with a full GPS constellation and six additional satellites operated in coordinateion with GPS.

The expected incidence of satellite failures and short-term outages (e.g., due to maneuvers) will increase the requirements. However, reliability studies indicate that only small increases in the number of visible satellites will be required. These studies need to be refined and extended with a specific focus on GLONASS, lower mask angles (5 degrees) and barometric aiding. Nevertheless, data available to date indicate that acceptable performance can be maintained with GPS plus one-fourth to one-half of the GLONASS constellation.

In US airspace, it is important to recognize that certificated GNSS receivers will incorporate barometric aiding, and will have additional ranging signals (and integrity information) from typically two additional geosynchronous spacecraft in the timeframe of Globalstar operations. The impact of ground-derived integrity data on system performance was not included in the analysis, but would be expected to significantly improve performance and reduce constellation requirements.

From an availability standpoint, there is no requirement to track GLONASS satellites operating on channel assignments above 1606 MHz. The current GLONASS frequency plan would provide a minimum of six spacecraft operating channels containing the C/A code below 1606 MHz. With antipodal assignments, GLONASS would offer an availability benefit of 12 operating spacecraft which is equivalent to approximately 4 geosynchronous spacecraft. However, as little as two geosynchronous spacecraft were shown previously (in Section 4) to satisfy primary means availability requirements in all phases of flight, as well as accuracy, availability, integrity and continuity requirements for en route, terminal area and NPA operations. (Note: Category I precision approach and surface operations require a differential overlay to enhance accuracy, and Category I precision approach also requires a differential overlay to enhance integrity. A WAAS would also provide additional ranging signals to enhance availability further.)

5.2 Conclusions

The conclusion of the MES impact assessment is that there is no operational impact in en route airspace, terminal area airspace, nonprecision approach and for surface operations. For Category I precision approach, continuity of service may be affected under a conservative set of analytic groundrules in cases where a GNSS user relies on GLONASS during the approach to provide needed additional integrity assurance for safe operations. This is not a likely mode of operation in the United States, although it may exist elsewhere. Furthermore, within the United States and adjacent regions, augmentations such as the WAAS are planned to be sufficient to support primary means navigation down to Category I minima without reliance on GLONASS.

For users who choose to depend on GLONASS in lieu of, or in addition to the WAAS, a potential interference mode exists. For these users, the presence of an active MES close to the extended runway centerline in a narrow region approximately 0.75 miles from runway threshold, operating in a shadowed mode (resulting in a high power MES transmission), could lead to a loss of GLONASS signal tracking and therefore loss of navigation system integrity , although navigation guidance is not lost at this point, or even necessarily degraded. In this situation, the user's avionics would potentially declare an integrity alarm that could lead to a missed approach.

Whether an integrity alarm is actually declared depends on numerous real-time parameters as well as the possible use of alternative navaids such as inertial reference systems, etc. We emphasize that almost any change in the underlying assumptions for this scenario would eliminate the possibility of signal tracking degradation. These changes include: (1) reliance on the WAAS; (2) reliance on WAAS ranging signals and on local DGPS correction and integrity broadcast; (3) less than full-power MES operations; (4) GNSS antenna directive gain less than -5 dBi toward the MES; (5) airframe or environmental shielding; (6) GNSS signals above minimum specified received power levels; or (7) GNSS receiver performance that exceeds the conservative ARINC 743A-1 J/S specifications.

Further analysis of continuity of service is recommended, with a specific focus on hybrid constellations including GLONASS snd GLONASS with WAAS, as well as the use of a mask angle of five degrees, and barometric aiding. This work can be performed on a theoretical basis with data currently available in the engineering community. Further refinement of the RFI link budgets would also be desirable, with specific focus on estimating GNSS antenna patterns below the horizontal and potential airframe shielding/shadowing parameters (if these can be measured or estimated).

Refinement of MES operating protocols would also be desirable, as would an assessment of actual signal tracking mechanisms within typical GNSS receivers. These assessments, taken together, should completely resolve all remaining concerns, and demonstrate that MES operations are not operationally significant to GNSS receivers operating at ranges of 100m or greater.

Assessment of MES-Induced RFI on Hybrid GPS/GLONASS Aviation Receivers

References

1. Brown, R. Grover et al., **Assesment of RAIM FDI Availability Using ARP Method of Screening Out Bad Geometries.** RTCA Paper No. 213-93. Special Committee 159-436. U.S. Department of Transportation, Volpe Transportation Systems Center, Cambridge, MA. Spring 1993.

2. **Global Positioning System Standard Positioning Service Signal Specification.** Department of Defense, Office of the Assistant Secretary of Defense for C3I/T&TC, The Pentagon, Washington, DC 20301-6000. November 1993.

3. Lee, Young, **RAIM Availability for GPS Augmented with Barometric Altimeter Aiding and Clock Coasting.** ***Navigation***, Journal of the ION, pps.179-198. Institute of Navigation, Alexandria, VA. Vol. 40, No. 2, Summer 1993.

4. **Minimum Aviation System Performance Standards, DGNSS Instrument Approach System: Special Category I (SCAT-I).** Report RTCA DO-217. Special Committee159 Working Group/4, RTCA Inc., 1140 Connecticut Ave. NW, Suite 1020 Washington, DC 20036. August 1993.

5. Misra, P. et al., **Receiver Autonomous Integrity Monitoring (RAIM) of GPS and GLONASS.** ***Navigation***, Journal of the ION, pps. 87-104. Institute of Navigation, Alexandria, VA. Vol. 40, No. 1, Spring 1993.

6. Phlong, W.S. and B.D. Elrod, **Availability Characteristics of GPS and Augmentation Alternatives.** ***Proceedings of the ION National Technical Meeting***, pps. 69-80, The Institute of Navigation, Alexandria, VA. January 1993.

Appendix A

Analytic Modifications Assuming Independent GPS And GLONASS Navigation Solutions

The body of this report assumed that all available pseudoranges were fused into a single navigation solution, with extra measurements (degrees of freedom) used to provide integrity in the form of fault detection and isolation. If separate navigation solutions are generated and compared "after the fact", overall operational availability will be degraded because a minimum of four satellites with good geometry are required from each constellation. With exactly four satellites from each constellation (i.e., eight signals total), a comparative algorithm can detect the presence of a problem, but cannot isolate it. The equivalent capability can be supported with a total of only five signals, in any mixture of GPS and GLONASS (in good geometry), with a fused algorithm. Similarly, fault detection and isolation requires a minimum of five satellites with good geometry from each constellation with a comparative algorithm, but only 6 satellites with good geometry for a fused algorithm.

The overall performance of comparative algorithms has not been investigated extensively by the aviation or navigation industry; however, preliminary assessments can be generated by interpreting the data for single constellations relative to their ability to support navigation with fault detection. If both constellations provide the ability to navigate with fault detection, the combination of the two will provide navigation with fault detection and isolation. This is true because a single failure can be detected in either constellation, and the remaining constellation is known (at that time) to be fault-free.

Young Lee[3] estimated that GPS+baro would provide an availability typically between 70% and 90% for navigation with fault detection, at five major airports distributed throughout CONUS. This estimate was for a navigation protection limit of 0.3 nmi (nonprecision approach), user mask angle of 7.5 degrees, and 21 operational satellites out of a 24 GPS constellation. The equivalent availability for terminal area operations was estimated at between 90% and 93%. If these results are assumed to hold for GLONASS as well, and the two constellations are assumed independent, then a comparative algorithm would yield availabilities of between 90% and 99% (roughly) for navigation with fault detection and isolation in terminal area and NPA operations. These availabilities do not satisfy primary means RNP. Thus, a comparative algorithm is not a viable alternative for GNSS receivers in the absence of other augmentations (such as WAAS).

RF interference modes will be insignificant from an availability and continuity standpoint for en route and terminal area operations (i.e., they will have an insignificant additional impact on availability). In these phases of flight, an aviation user should be outside even the conservative threat region around an MES. As noted previously, an aircraft should not be flying below 500 feet (152m.) above terrain in populated areas. Even if an aircraft is actually flying this low, and passes directly over an MES operating at full power, exposure times for both GPS and GLONASS are less than the time to alarm in these domains, indicating robust performance.

As with a fusion-type algorithm, RF interference modes can potentially affect Continuity of Service for NPA (note that availability would be assessed at the beginning of the approach, which is at sufficient altitude to preclude any effect from a ground-based MES). When RF interference is considered, performance levels for continuity will be driven toward the values calculated in

---

1. Y. Lee, **RAIM Availability for GPS Augmented with Barometric Altimeter Aiding and Clock Coasting**, ***Navigation, Journal of The Institute of Navigation***, Summer 1993.